

THE MOS CONTROLLED THYRISTOR (MCT) AS AN ON-OFF CAPACITOR BANK SWITCH *

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ABSTRACT

The MCT^{1,2} is a new class of thyristor which can be closed or opened with control signals and control energies equivalent to those required to charge and discharge the gate capacitance of a power MOSFET. The device can be thought of as a conventional thyristor in which the resistance of the emitter shorts is controllable by means of a MOS gate. The MCT structure has the power handling capability of a conventional or Gate Turn-Off (GTO) thyristor of equivalent size.

MCTs presently available are limited to blocking voltages of 500 V and controllable currents of 100 A. We have tested MCTs as output on-off switches in capacitive pulser circuits with both resistive and inductive loads. Significant voltages, up to 1.5kV, were obtained by operating the devices in series. A brief description of the MCT is presented. Experimental results are presented which describe its switching characteristics when operated alone and as part of a series array. The MCT's future potential is briefly evaluated.

INTRODUCTION

The MCT is potentially important to the field of pulse power primarily because of its ability to repetitively interrupt current without the need for commutation circuitry and without significant power being consumed by control circuits. The device can be thought of as a conventional thyristor in which the resistance of the emitter shorts is controllable by means of an MOS gate. The resulting device has the power handling capability and low conduction loss of a thyristor combined with the ability to be easily turned off.

The highest power MCTs which we have tested are capable of blocking 500 V and controlling 100 A. These devices, therefore, would be of little interest if not for the fact that MCT topology can be scaled up to significantly higher powers. Blocking voltages of 2.5 kV have been demonstrated and controllable current densities of up to 500 A/cm² of active device area have been observed.³ Within a year, prototype MCT modules capable of blocking 2.5 kV and controlling 1000 A will have been assembled.

Figure 1 shows a representative device cross-section of an MCT unit cell containing both on- and off-FETs, along with a simplified equivalent circuit model. Only about 4% of the cells in our MCTs contain on-FETs, and as shown by the cross-section only one gate terminal is required to control both FETs.

Turn-on of the MCT is accomplished by closing the on-FET and holding the off-FET open. This provides base drive from the externally applied anode-cathode voltage, V_k to the lower (wide base) transistor which in turn provides base drive to the upper (narrow base) transistor. As in any thyristor, when sufficient base drive is present such that the sum of the transistor gains is greater than 1, the MCT latches on and the base drives continue to increase until the device is fully on. At this point the forward voltage drop of the thyristor is approximately equal to that of a single forward biased p-n junction.

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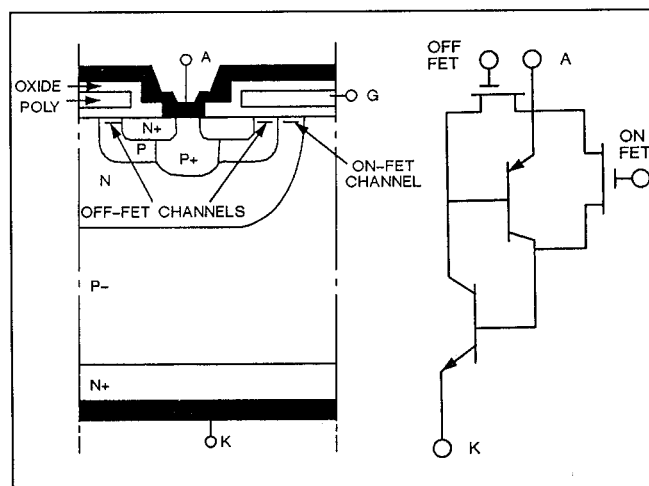


Figure 1: Cross-section of MCT unit cell and equivalent circuit.

The MCT's ability to turn off is its most interesting feature, but the turn-off process can be described quite simply. Once the thyristor is latched, the state of the on-FET is no longer significant and can therefore be ignored. Turn-off is accomplished by gating the off-FET closed. This shorts the base-emitter junction of the off narrow base transistor, effectively turning the upper transistor (refer to figure 1, equivalent circuit) off. This deprives the wide-base transistor of base drive and it begins to turn off. MCT anode current fall-time is then largely determined by carrier recombination in the wide base.

The off-FET must conduct full anode current for a short time during turn-off. It is therefore important that the off-FET be fabricated such that it has a low drain to source ON resistance, $R_{ds(on)}$. The MCT's turn off capability is determined by the density of off-FET channels and their $R_{ds(on)}$. Fortunately, $R_{ds(on)}$ can be made very small because the FET does not need to have a very high voltage blocking capability. In fact, the highest voltage the off-FET will ever see is the diode drop of the forward biased base-emitter junction of the narrow base transistor, usually less than 1 V.

The gate drive requirements of the MCT can be simply explained in terms of controlling the on- and off-FETs. The FETs are controlled by a gate signal, V_g which is referenced to the MCT anode. The MCTs described here have n-channel off-FETs and p-channel on-FETs. Both FETs are enhancement mode devices, that is if $V_g = 0$, both FETs are open. This condition leaves the MCT susceptible to 'noise' or dV/dt turn-on as is the case in any thyristor without emitter shorts. It is therefore preferred to bias the MCT off by holding V_g positive. With the off-FET thus held closed, the MCT is virtually immune to dV/dt turn-on. The MCT is closed by switching V_g to a negative value, opening the off-FET and closing the on-FET. The device is opened by returning V_g to a positive level sufficient to close the off-FET.

Signal levels of $V_g = +12V$ and $V_g = -5V$ are used to turn the MCT off and on respectively. The off-FET is driven well above its gate threshold voltage in order to minimize $R_{ds(on)}$, thus maximizing turn-off capability. Turn-on is not as critical. The MCT gate is almost a pure capacitance. It is insensitive to load and draws no current once charged. Our test devices have gate capacitances

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ranging from about 7.5 to 8.0 nF. The maximum gate energy, therefore, required to switch the MCT (either on or off) is about 1.16 microjoules, from $1/2 CV^2$. These devices will turn off up to 100 A at room temperature. Their forward repetitive surge (pulse) current has not yet been determined but is expected to be about 500 A.

To switch the MCT gate in 100 nS requires a peak current of only about 1.36 A, from $C dV/dt$. In contrast, a Gate Turn-Off thyristor (GTO) requires that 20% to 35% of the anode current be diverted through the gate drive circuit for the entire duration of turn-off, usually 2 to 20 microseconds depending on the specific GTO.

DISCUSSION

An experimental program was devised to evaluate the MCT's potential application to pulse power. This is a unique effort as the device will primarily find application in power supply, motor control, power distribution, and other AC circuits. It was necessary to determine if MCTs designed for AC circuits would be directly applicable to pulse modulators, and if not, could a 'pulse power' MCT be designed.

Device characterization was conducted in various circuits using various MCT gate drivers, but the important features of the test circuit are illustrated in figure 2. The storage capacitor and switch 'on' time (pulse width) were chosen such that the MCT was always required to open to at least 95% of the initial charge voltage. Load inductance was varied from zero, i.e. no inductance deliberately added, to 22 microhenries. Load resistance was varied to maintain peak currents at or below the turn-off rating of the MCT. A snubber circuit consisting of a small capacitor (0.05 to 0.1 uF) in series with a 1.0 to 1.5 ohm damping resistor was placed across each MCT during series operation to act as a voltage divider and help prevent overvoltage during turn-off due to circuit inductance. The gate drive signal was always chosen so as not to limit MCT performance. The actual gate drive circuits will not be discussed here. Characterization included verifying manufacturer's specifications as well as measuring rise and fall times of anode current and voltage across the device with various loads.

The first MCTs tested were experimental devices fabricated at General Electric's Corporate R&D Center (GECRD). The most significant switching data obtained with these devices was from a group designated as process Lot #9. MCTs currently under test are pre-production prototypes manufactured at GE's (formerly RCA's presently Harris Corp's) Mountaintop, PA semiconductor facility. They carry the part number TA9789A, but for simplicity will be referred to as Mountaintop or M-MCTs.

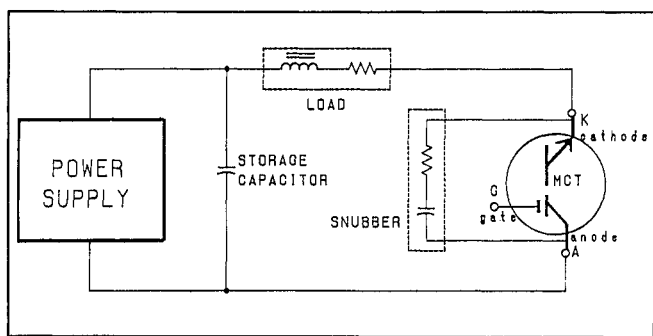


Figure 2: Basic MCT Test Circuit

The lot #9 MCTs were rated by GE at room temperature and at a junction temperature of 200°C. At 25°C a typical device rating was static blocking or breakdown voltage, V_{br} , of 600 V and a controllable current, I_{off} , of >60 A. We were able to verify V_{br} . The best dynamic results (in a non-inductive circuit) which were recorded showed a lot #9 device opening 48 A to block 450 V. The typical 200°C ratings were nominally $V_{br} = 500$ V and $I_{off} = 20$ A. No tests were conducted at elevated temperature, but neither were any efforts made to heat sink or cool the devices. The lot #9 devices typically closed in about 1 microsecond and opened in 8 to 10 microseconds with a non-inductive load.

The M-MCTs are all rated at a junction temperature of 150°C. Their nominal V_{br} is 500V but with a 'safe operating voltage', V_{soa} of about 300 V. The rated I_{off} is 50 A at 150°C. Once again, no tests were conducted at elevated temperature. Our best dynamic result, with respect to these ratings, was $I_{off} = 98$ A with the MCT recovering to block 285 V. The M-MCTs switch somewhat faster than the lot #9s, closing in about 600 ns and opening in 0.8 to 2.0 microseconds, with that range being due to varying circuit inductance, not device to device variation.

One significant restriction of MCT technology is blocking voltage. As with other thyristors, a practical limit for forward blocking voltage (V_{br}) in the foreseeable future is 5 to 6 kilovolts. If the devices are to be optimized for parameters other than blocking voltage, e.g. fast opening times or low conduction losses, V_{br} could be significantly lower. In addition, the safe operating voltage is significantly less than V_{br} (60% in the M-MCTs) and V_{soa} can not be expected to scale linearly with V_{br} . These factors led to an experimental program for operating MCTs in series.

The series testbed is essentially identical to figure 2 except that no added inductance was used and that where a single MCT and snubber are shown, up to six (6) were placed in series.

Series operation was first accomplished with lot #9 MCTs by independently adjusting the position (in time) of the leading and trailing edge of each gate pulse in order to insure good voltage sharing across the series stack. This was necessary because the devices varied in switching speeds and trigger delays. Next, lot #9 devices were hand picked for uniformity of switching speed and it was demonstrated that they could operate in series with gates synchronized. Based on this result, the testbed for running 6 M-MCTs in series was designed with no provision for individual gate timing.

EXPERIMENTAL RESULTS

A number of M-MCTs were characterized with resistive and inductive loads over an operating range of 50 to 300 volts at turn-off currents of up to 100 amps. Voltage and current were monitored with Tektronix voltage probes, Pearson and Tektronix current transformers, and calibrated current viewing resistors manufactured by T & M Research. The waveforms were displayed and stored on a Tek 7854 digital oscilloscope. Some of the scope traces have been stored and reproduced in laboratory computer systems using a Tek software package which allows a PC to communicate with the 7854. Rise and fall times, power dissipation calculations, etc., were performed using the scope to manipulate the digitized waveforms.

Figure 3 shows typical waveforms obtained with an M-MCT in the circuit of figure 2 with a 3 ohm non-inductive load. The upper trace shows the cathode voltage waveform across the MCT. The vertical scale is 100 V/div. The operating voltage is 260 V. The sweep speed is 2 μ s/div. The 10%-90% time for fall of cathode potential across the device, t_{fv} , is 0.405 μ s and the 10%-90% time for reapplication of cathode potential, t_{rev} , is 1.5 μ s. The lower trace is the load current. The peak current, i_p , is 76.9 A. The 10%-90% risetime of the current, t_{rc} , is 0.716 μ s and the 10% - 90% falltime, t_{fc} , is 1.492 μ s.

Several devices were studied to determine their performance in an inductive circuit. Figure 4 shows the voltage across the MCT when operated in the circuit of figure 2 with a load consisting of 3 ohms in series with 6.3 uH and no snubber circuit. V_K is 100 volts and t_{fv} is 0.640 μ s. The time for reapplication of cathode potential is 390 ns, but that is the time to the first crossing of the 100 volt level. Since an inductor current is being interrupted, a voltage spike is imposed on the cathode of the opening MCT. The overvoltage reaches 307 V, over 3 times the supply voltage, V_K . The 10%-90% risetime to 307 V is 355 ns. The overshoot then decays to the supply voltage in about 3.5 μ s. Note that this represents a dV/dt of 8.6×10^8 V/s and the MCT does not turn on.

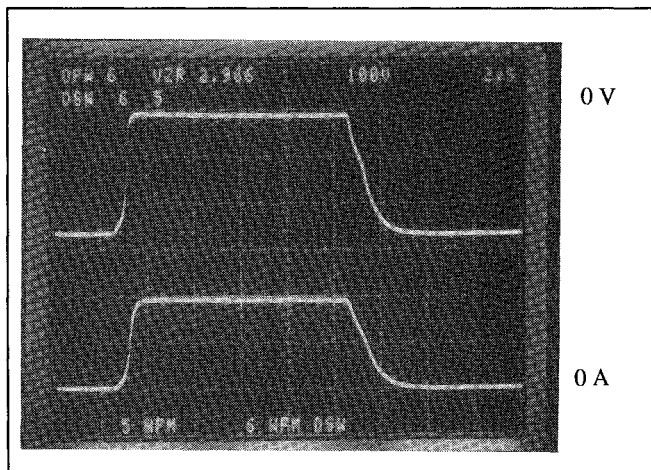


Figure 3: MCT Voltage (upper trace) and Load Current with 3 ohm non-inductive load. Scales shown are correct, lower trace vertical is 40 A/div.

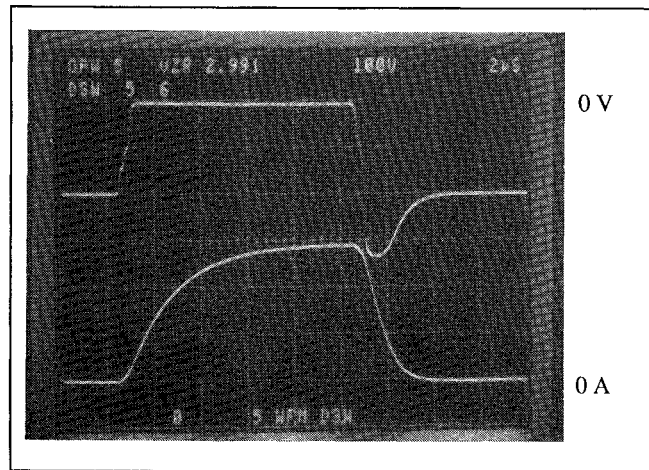


Figure 5: MCT Voltage (upper trace) and Load Current with Inductive Load. Scales shown are correct. Lower trace vertical is 20 A/div.

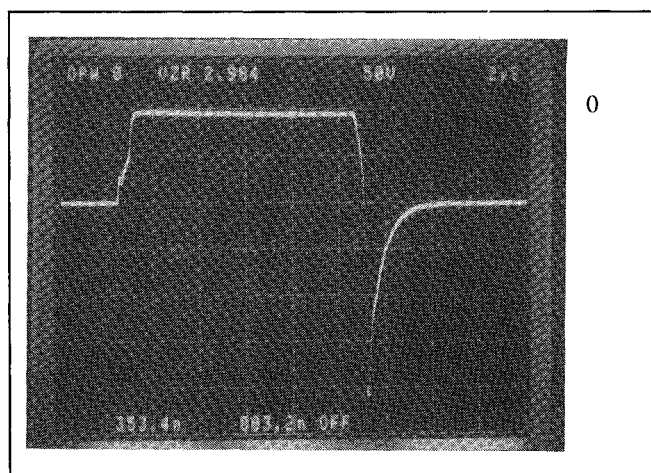


Figure 4: Voltage Across MCT with Inductive Load.

Figure 5 shows data taken at a V_K of 200 V with the same load as in Figure 4. On the upper trace, the voltage across the switch, t_{fv} is 0.541 μ s and the t_{trv} to 200 V is 0.430 μ s. The cathode potential continues to rise until reaching the MCT's "self-clamp" voltage, V_{sc} , of 330 V and then decays to the supply voltage in about 4 μ s. The lower trace shows the circuit current measured at the MCT cathode. The peak current is 58 A and the rise and fall times are 4.4 μ s and 1.6 μ s respectively. The measured current risetime agrees with the calculated circuit risetime of 4.61 μ s. Results of inductive turn-off with another MCT and a load consisting of 6 ohms in series with 9.26 μ H are shown in Table I. The parameter of prime interest is V_{sc} which rises from 307 V to 341 V as V_K is increased from 100 V to 300 V, with peak current increasing from 16 A to 47.4 A.

Any opening switch is stressed considerably during turn-off, particularly in an inductive circuit. The power/energy dissipation was calculated and plotted for the case of inductive turn-off (figure 5) and at similar operating conditions with the inductor shorted. Figure 6 shows the power dissipation vs time, obtained by using the digital oscilloscope to multiply the voltage and current waveforms. The upper trace shows dissipation with a resistive load (3 ohm) and the lower trace shows the effect of adding a 6.3 μ H inductor. The waveforms are normalized to the same vertical scale, 5000 watts/div, for display. Table II shows the dissipation for each case broken out into turn-on, steady state conduction, and turn-off dissipation.

Table I

RL Ω	L μ H	V_K V	Voltage		V_{sc} V	Current		
			t_{fv} μ s	t_{trv} μ s		t_{trc} μ s	t_{ffc} μ s	i_p A
6	9.26	100	0.584	0.263	307	3.46	1.03	16.0
				(100 V)				
		150	0.523	0.300	316	3.40	1.13	23.7
				(150 V)				
		200	0.496	0.350	321	—	—	—
				(200 V)				
		250	0.470	0.397	327	3.41	1.69	39.5
				(250 V)				
		300	0.475	0.458	341	3.41	2.20	47.4
				(300 V)				

Calculated $t_{trc} = 3.4 \mu$ s

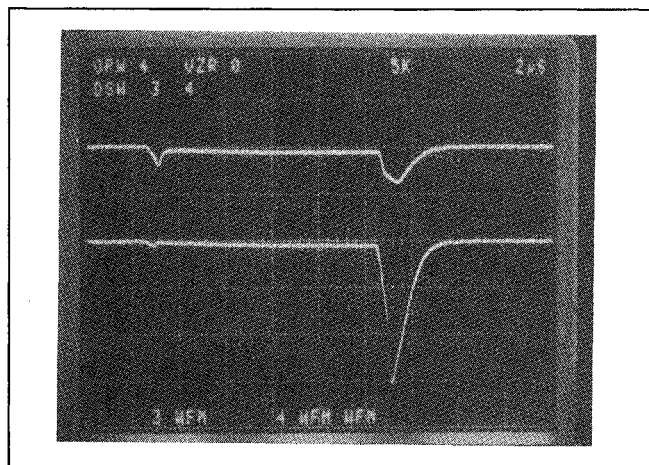


Figure 6: MCT Power Dissipation with a Resistive Load (upper trace) and an Inductive load. Zero for the lower trace is center line. The upper trace has its zero at two divisions above center.

Table II
Single Pulse Power Dissipation in MCT

Conditions

Load (R_L)	3Ω	$3\Omega + 6.28 \mu\text{H}$
Pulse Width (tp)	$10 \mu\text{s}$	$10 \mu\text{s}$
Operating Voltage (V_k)	200V	200V
Peak Current (i_p)	59A	58A

Dissipation

Commutation-On	1.0 mJ	0.14 mJ
Steady State	3.8 mJ	3.05 mJ
Commutation-Off	4.8 mJ	15.50 mJ
Total	9.6 mJ	18.70 mJ

The commutation-on dissipation of the purely resistive case is 7 times that of the inductive case. This is expected as the rise of current in the device is 9 times faster without the inductor and t_{fv} is comparable. Therefore, $I * V$ during turn-on is much greater. The steady state dissipation is roughly equivalent for both cases, given the accuracy of the data acquisition system. The dissipation in the MCT during turn-off is 10.7 mJ greater with the addition of the 6.3 uH inductor to the load. This is expected as the inductor applies a large voltage across the MCT during turn-off as shown in figures 4 & 5. The increased dissipation corresponds almost exactly to the energy stored in the inductor at the peak current, $(I^2 * L)/2 = 10.6 \text{ mJ}$.

Figure 7 shows operation of 6 M-MCTs in series at a V_k of 1500 V. A 56 ohm non-inductive load was used and the MCT stack controlled 26 A. Initially, a snubber circuit consisting of a 0.05 μf capacitor damped by a 1.0 ohm resistor was connected across each MCT. After low voltage testing, capacitance was added across some of the MCTs to improve voltage division. The largest snubber capacitor was 0.07 μf .

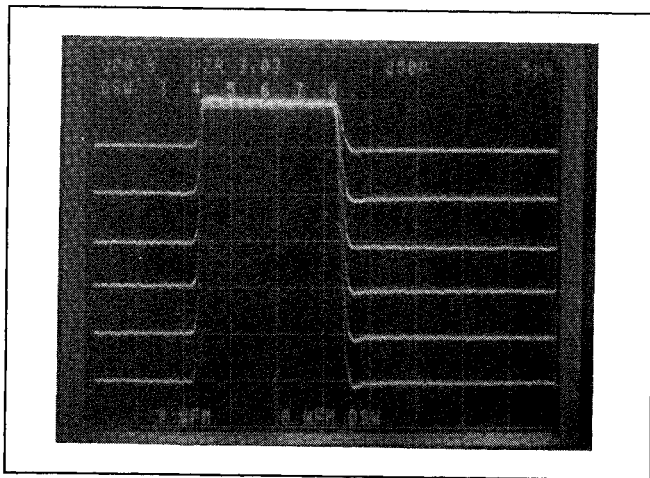


Figure 7: Voltages Across 6-MCT Series Stack.

Each trace in figure 7 shows the voltage between one MCT cathode and ground. Ground on the photograph is 3 divisions above center line. The vertical scale is 250 volts/div and the horizontal scale is $5 \mu\text{s}/\text{div}$. Peak power delivered to the load was about 38 kilowatts. Figure 8 shows the load current controlled by the MCT stack. The peak current is 26 A. The rise and fall times are $0.848 \mu\text{s}$ and $1.6 \mu\text{s}$ respectively as noted on the photo. The greatest engineering challenge to series operation was the design of gate driver circuits which floated off circuit ground. Each gate driver common was connected to its MCT's anode. The final driver design used batteries for isolated power and fiber optics for all control signals.

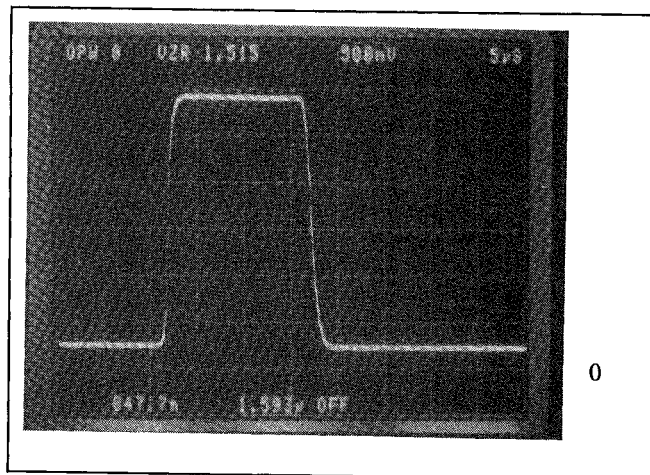


Figure 8: Load Current with 6 - MCT Stack. Vertical Scale is 5 A / div

CONCLUSIONS

The MCT is at a very early stage of development and the devices described here are considered to be little more than experimental. Even so, the device has demonstrated impressive capabilities. It has been demonstrated that the MCT can interrupt current in both resistive and inductive circuits while consuming insignificant control power. So far, these prototype devices have been operated at peak powers of up to 20 kW at repetition rates of up to 10 kHz. The newer devices close in as fast as 300 nS and open in less than 2 μs (worst case). The control energy required to switch the MCT either on or off is about 1.0 μJ . Series operation of up to six devices has been demonstrated in a non-inductive circuit with minimal device derating and relatively small snubber circuits. Within a year, prototype MCT modules, capable of blocking 2.5 kV and controlling 1000 A, will be assembled. These devices, operated in series and parallel arrays, will play a significant role in the future of repetitive pulse power systems.

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